False Vacuum Higgs Inflation and the Graviweak Unification

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Abstract

In the present paper we develop a model of the Higgs inflation based on the non-minimal coupling of the Higgs boson to gravity predicted by Graviweak Unification. But later we get rid of the non-minimal coupling to gravity by making the conformal transformation from the Jordan frame to the Einstein frame. We construct a self-consistent $Spin(4,4)$-invariant model of the unification of gravity with weak $SU(2)$ interactions in the assumption of the existence of visible and invisible sectors of the Universe. Assuming the interaction between the ordinary and mirror Higgs fields, we develop a special Hybrid model of inflation. According to this model, the inflaton starts trapped from the false vacuum of the Universe at the Higgs field VEV $v \sim 10^{18}$ GeV (in the visible world). Then the inflations of the two Higgs doublet fields, visible ϕ and mirror ϕ', lead to the emergence of the Standard Model vacua at the Electroweak scales with the Higgs boson VEVs $v_1 \approx 246$ GeV and $v'_1 = \zeta v_1$ in the visible and invisible worlds, respectively. Considering the results of cosmology and calculating the number of e-folds N^*, we predict $\zeta \simeq 100-115$ for $N^* \simeq 50-60$, in agreement with previous results of the model with broken mirror parity. We also consider RGEs, taking into account the mixing term - the interaction between the ordinary and mirror Higgs bosons, assuming the smallness of the mixing coupling.

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1 Introduction

In Ref. [1] (see also [2, 3]) we suggested a model of the Higgs inflation, which follows from the unification of the gravity, weak $SU(2)$ gauge and Higgs fields [4, 5]. In this model we also used the Sidharth's ideas about the existence of a discrete space-time at the Planck scale with non-commutative geometry, predicting an almost zero cosmological constant [6–8].

Recently there has been a lot of interest in using the Higgs boson as an inflaton in the context of the non-minimal coupling to gravity [9–20]. The papers [20–25] investigated how the false vacuum could be used to explain the inflationary phase of the Universe. Inflation from a local minimum develops a model with a graceful exit to the radiation-dominated era of the Universe. The hypothesis that the inflation took place in the SM false vacuum is consistent with a narrow range of values of the Higgs boson mass, which subsequently turned out to be compatible with the experimental range indicated by ATLAS and CMS [26, 27].

In the present paper we developed the model of the Higgs inflation using the Graviweak Unification [4], which predicts the non-minimal coupling to gravity. We tried to calculate the parameters of theory, which lead to the self-consistent inflationary model. Assuming the interaction between the ordinary and mirror Higgs fields φ and φ', we considered a special Hybrid model of the inflation by A. Linde [28]. According to this inflationary model, a scalar field (inflaton) starts trapped from the false vacuum of the Universe at the Higgs fields VEV $v \sim 10^{18}$ GeV.

A model of unification of gravity with the weak $SU(2)$ gauge and Higgs fields was constructed in Ref. [4], in accordance with Ref. [5]. Previously gravi-weak and gravi-electro-weak unified models were suggested in Refs. [29–31].

In the present investigation we imagine that at the early stage of the evolution of the Universe the GUT-group was broken down to the direct product of gauge groups of the internal symmetry $U(4)$ and $Spin(4,4)$-group of the Graviweak Unification.

In the assumption that there exist visible and invisible (hidden) sectors of the Universe, we presented the hidden world as a Mirror World (MW) with a broken Mirror Parity (MP), and gave arguments that MW is not identical to the visible Ordinary World (OW). We started with an extended $\mathfrak{g} = \mathfrak{spin}(4,4)_L$-invariant Plebanski action in the visible Universe, and with $\mathfrak{g} = \mathfrak{spin}(4,4)_R$-invariant Plebanski action in the MW. Then we have shown that the Graviweak symmetry breaking leads to the following sub-algebras: $\tilde{\mathfrak{g}} = \mathfrak{s}l(2,C)_L^{(grav)} \oplus \mathfrak{s}u(2)_L$ – in the ordinary world, and $\tilde{\mathfrak{g}}' = \mathfrak{s}l(2,C)'^{(grav)}_R \oplus \mathfrak{s}u(2)'_R$ – in the hidden world. These sub-algebras contain the self-dual left-handed gravity in the OW, and the anti-self-dual right-handed gravity in the MW. Finally, at low energies, we obtain a Standard Model (SM) group of symmetry and the Einstein-Hilbert's gravity. In this approach we have developed a model of inflation, in which the inflaton σ, being a scalar $SU(2)$-triplet field, decays into the two Higgs $SU(2)$ doublets of the SM: $\sigma \to \phi^\dagger\phi$, and then the interaction between the ordinary and mirror Higgs fields (induced by gravity) leads to the hybrid model of the inflation.

In Section 2 we considered the Plebanski's theory of gravity, in which fundamental fields are 2-forms, containing tetrads, spin connections and auxiliary fields. Then we have used an extension of the Plebanski's formalism of the 4-dimensional gravitational theory, and in Section 3 we constructed the action of the Graviweak unification model, described by the overall unification parameter g_{uni}. The existence of de Sitter solutions at the early time of acceleration era of the Universe is discussed in Subsection 3.1. The parameters of the Graviweak unification model (Newton gravitational constant, G_N, bare cosmological constant, Λ_0, and bare coupling constant of weak interaction, g_W) were estimated in Subsection 3.2. It was shown that the GWU Lagrangian includes the non-

minimal coupling with gravity. We see that at the Planck scale "second minimum", the Higgs field φ can be represented as $\varphi = v - \sigma$, where the real scalar field σ is an inflaton. At the Planck scale vacuum with its VEV equal to v, the inflaton field is zero ($\sigma = 0$), and then increases with the falling of the field φ. Considering the expansion of GWU Lagrangian in powers of small values of σ/v, we get rid of the non-minimal coupling to gravity by making the conformal transformation from the Jordan frame to the Einstein frame. Section 4 is devoted to the Multiple Point Model (MPM), which allows the existence of several minima of the Higgs effective potential with the same energy density (degenerate vacua). The MPM assumes the existence of the SM itself up to the scale $\sim 10^{18}$ GeV, and predicts that there exist two degenerate vacua into the SM: the first one – at the Electroweak (EW) scale (with the VEV $v_1 \simeq 246$ GeV), and the second one – at the Planck scale (with the VEV $v = v_2 \sim 10^{18}$ GeV). In Section 5 we considered the existence in the Nature of the Mirror World (MW) with a broken Mirror Parity (MP): the Higgs VEVs of the visible and invisible worlds are not equal,[1] $\langle\phi\rangle = v$, $\langle\phi'\rangle = v'$ and $v \neq v'$. The parameter characterizing the violation of the MP is $\zeta = v'/v \gg 1$. In Section 6 we have used the Sidharth's prediction about the existence of a discrete space-time at the Planck scale, showing that the idea of non-commutativity predicts an almost zero cosmological constant. In Section 7 we suggest a model of the Higgs inflation using the GWU action with Lagrangian in the Einstein frame. Taking into account the interaction between the initial ordinary and mirror Higgs fields: $\alpha_\varphi(\varphi^\dagger\varphi)(\varphi'^\dagger\varphi')$, we constructed a hybrid model of the Higgs inflation in the Universe. According to this model, a scalar field φ starts trapped from the "false vacuum" of the Universe at the value of the Higgs field's VEV $v = v_2 \sim 10^{18}$ GeV. Using new fields $\varphi = v - \sigma$ and $\varphi' = v' - \sigma'$, we assume that a scalar field σ, being an inflaton, starts trapped from the "false vacuum" of the Universe at the value of the Higgs field's VEV $v = v_2 \sim 10^{18}$ GeV. But then during inflation the field σ decays into the two Higgs doublets of the SM: $\sigma \to \phi^\dagger\phi$. Considering the interaction $\alpha_\phi(\phi^\dagger\phi)(\phi'^\dagger\phi')$ between the visible and mirror Higgs doublet fields ϕ and ϕ' , we show that this interaction leads to the emergence of the SM vacua at the EW scales with the Higgs boson VEVs $v_1 \approx 246$ GeV and $v'_1 = \zeta v_1$ in the visible and invisible worlds, respectively. Here we also use the Sidharth's prediction about the existence of the non-commutative geometry at the Planck scale which predicts an almost zero cosmological constant. In Subsection 7.1 we investigate the agreement of our GWU model of the Higgs inflation with modern predictions of cosmology. Calculating the expression for a number of e-folds N^*, we estimate the MW parameter ζ. We obtained: $\zeta \simeq 100 - 115$ for $N^* \simeq 50 - 60$, in accordance with estimations of the previous references, predicted $\zeta \sim 100$. In Section 8 we presented the calculation of the renormalization group equations (RGEs) in the assumption that there exists the interaction between the ordinary and mirror Higgs bosons. We confirmed the small values of parameters λ' and α_ϕ, which do not change essentially the results of the 2-, or 3-loop calculations of the Higgs mass. Section 9 contains Summary and Conclusions.

2 Plebanski's formulation of General Relativity

General Theory of Relativity (GTR) was formulated by Einstein as dynamics of the metrics $g_{\mu\nu}$. Later, Plebanski [32] and other authors (see for example [33, 34]) presented GTR in the self-dual approach, in which fundamental variables are 1-forms of connections A^{IJ} and tetrads e^I :

$$A^{IJ} = A^{IJ}_\mu dx^\mu, \qquad e^I = e^I_\mu dx^\mu. \tag{1}$$

[1] In this paper the superscript 'prime' denotes the M- or hidden H-world.

Also 1-form $A = \frac{1}{2}A^{IJ}\gamma_{IJ}$ is used, in which generators γ_{IJ} are products of generators of the Clifford algebra $Cl(1,3)$: $\gamma_{IJ} = \gamma_I\gamma_J$. Indices $I, J = 0, 1, 2, 3$ belong to the spacetime with Minkowski's metrics $\eta^{IJ} = \mathrm{diag}(1, -1, -1, -1)$, which is considered as a flat space, tangential to the curved space with the metrics $g_{\mu\nu}$. In this case connection belongs to the local Lorentz group $SO(1,3)$, or to the spin group $Spin(1,3)$. In general case of unifications of gravity with the $SU(N)$ or $SO(N)$ gauge and Higgs fields (see [5]), the gauge algebra is $\mathfrak{g} = \mathfrak{spin}(p,q)$, and we have $I, J = 1, 2...p+q$. In our model of unification of gravity with the weak $SU(2)$ interactions we consider a group of symmetry with the Lie algebra $\mathfrak{spin}(4,4)$. In this model indices I, J run over all 8×8 values: $I, J = 1, 2.., 7, 8$.

For the purpose of construction of the action for any unification theory, the following 2-forms are also considered:

$$B^{IJ} = e^I \wedge e^J = \frac{1}{2}e^I_\mu e^J_\nu dx^\mu \wedge dx^\nu, \qquad F^{IJ} = \frac{1}{2}F^{IJ}_{\mu\nu}dx^\mu \wedge dx^\nu,$$

where $F^{IJ}_{\mu\nu} = \partial_\mu A^{IJ}_\nu - \partial_\nu A^{IJ}_\mu + [A_\mu, A_\nu]^{IJ}$, which determines the Riemann-Cartan curvature: $R_{\kappa\lambda\mu\nu} = e^I_\kappa e^J_\lambda F^{IJ}_{\mu\nu}$. Also 2-forms of B and F are considered :

$$B = \frac{1}{2}B^{IJ}\gamma_{IJ}, \qquad F = \frac{1}{2}F^{IJ}\gamma_{IJ}, \qquad F = dA + \frac{1}{2}[A, A]. \tag{2}$$

The well-known in literature Plebanski's BF-theory is submitted by the following gravitational action with nonzero cosmological constant Λ:

$$I_{(GR)} = \frac{1}{\kappa^2}\int \epsilon^{IJKL}\left(B^{IJ} \wedge F^{KL} + \frac{\Lambda}{4}B^{IJ} \wedge B^{KL}\right), \tag{3}$$

where $\kappa^2 = 8\pi G_N$, G_N is the Newton's gravitational constant, and $M_{Pl}^{red.} = 1/\sqrt{8\pi G_N}$.

Considering the dual tensors:

$$F^*_{\mu\nu} \equiv \frac{1}{2\sqrt{-g}}\epsilon^{\rho\sigma}_{\mu\nu}F_{\rho\sigma}, \quad A^{\star IJ} = \frac{1}{2}\epsilon^{IJKL}A^{KL},$$

we can determine self-dual (+) and anti-self-dual (-) components of the tensor A^{IJ}:

$$A^{(\pm)\,IJ} = \left(\mathcal{P}^\pm A\right)^{IJ} = \frac{1}{2}\left(A^{IJ} \pm iA^{\star IJ}\right). \tag{4}$$

Two projectors on the spaces of the so-called self- and anti-self-dual tensors

$$\mathcal{P}^\pm = \frac{1}{2}\left(\delta^{IJ}_{KL} \pm i\epsilon^{IJ}_{KL}\right)$$

carry out the following homomorphism:

$$\mathfrak{so}(1,3) = \mathfrak{sl}(2,C)_R \oplus \mathfrak{sl}(2,C)_L. \tag{5}$$

As a result of Eq. (5), non-zero components of connections are only $A^{(\pm)i} = A^{(\pm)0i}$. Instead of (anti-)self-duality, the terms of left-handed (+) and right-handed (-) components are used.

Plebanski [32] and other authors [33,34] suggested to consider a gravitational action in the (visible) world as a left-handed $\mathfrak{sl}(2,C)^{(grav)}_L$- invariant action, which contains self-dual fields $F = F^{(+)i}$ and $\Sigma = \Sigma^{(+)i}$ (i=1,2,3):

$$I_{(grav)}(\Sigma, A, \psi) = \frac{1}{\kappa^2}\int\left[\Sigma^i \wedge F^i + \left(\Psi^{-1}\right)_{ij}\Sigma^i \wedge \Sigma^j\right]. \tag{6}$$

Here $\Sigma^i = 2B^{0i}$, and Ψ_{ij} are auxiliary fields, defining a gauge, which provides equivalence of Eq. (6) to the Einstein-Hilbert gravitational action:

$$I_{(EG)} = \frac{1}{\kappa^2}\int d^4x\left(\frac{R}{2} - \Lambda\right), \tag{7}$$

where R is a scalar curvature, and Λ is the Einstein cosmological constant.

3 Graviweak unification model

On a way of unification of the gravitational and weak interactions we considered an extended $\mathfrak{g} = \mathfrak{spin}(4,4)$-invariant Plebanski's action:

$$I(A,B,\Phi) = \frac{1}{g_{uni}} \int_{\mathfrak{M}} \left\langle BF + B\Phi B + \frac{1}{3} B\Phi\Phi\Phi B \right\rangle, \qquad (8)$$

where $\langle ... \rangle$ means a wedge product, g_{uni} is an unification parameter, and Φ_{IJKL} are auxiliary fields.

Varying the fields A, B and Φ, we obtained the field equations:

$$\mathcal{D}B = dB + [A,B] = 0, \qquad (9)$$

where $\mathcal{D}$ is the covariant derivative,

$$\mathcal{D}_\mu^{IJ} = \delta^{IJ}\partial_\mu - A_\mu^{IJ},$$

and

$$F = -2\left(\Phi + \frac{1}{3}\Phi\Phi\Phi\right) B, \qquad (10)$$

$$B^{IJ}B^{KL} = -\frac{1}{16} B^{IJ} \Phi^{KL}_{MN} \Phi^{MN}_{PQ} B^{PQ}. \qquad (11)$$

The first equation describes the dynamics, while last two determine B and Φ respectively. Here we assumed that the cosmological constant is zero: $\Lambda = 0$.

Having considered the equations of motion, obtained by means of the action (8), and having chosen a possible class of solutions, we can present the following action for the Graviweak unification (see details in Refs. [4, 5]):

$$I(A,\Phi) = \frac{1}{8g_{uni}} \int_{\mathfrak{M}} \langle \Phi F F \rangle, \qquad (12)$$

where

$$\langle \Phi F F \rangle = \frac{d^4x}{32} \epsilon^{\mu\nu\rho\sigma} \Phi_{\mu\nu}{}^{\varphi\chi IJ}{}_{KL} F_{\varphi\chi IJ} F_{\rho\sigma}{}^{KL}, \qquad (13)$$

and

$$\Phi_{\mu\nu}{}^{\rho\sigma ab}{}_{cd} = (e^f_\mu)(e^g_\nu)\epsilon_{fg}{}^{kl}(e^\rho_k)(e^\sigma_l)\delta^{ab}_{cd}. \qquad (14)$$

A spontaneous symmetry breaking of our new action that produces the dynamics of gravity, weak $SU(2)$ gauge and Higgs fields, leads to the conservation of the following sub-algebra:

$$\tilde{\mathfrak{g}} = \mathfrak{s}l(2,C)_L^{(grav)} \oplus \mathfrak{s}u(2)_L.$$

Considering indices $a, b \in \{0,1,2,3\}$ as corresponding to $I, J = 1,2,3,4$, and indices m, n as corresponding to indices $I, J = 5,6,7,8$, we can present a spontaneous violation of the Graviweak unification symmetry in terms of the 2-forms:

$$A = \frac{1}{2}\omega + \frac{1}{4}E + A_W,$$

where $\omega = \omega^{ab}\gamma_{ab}$ is a gravitational spin-connection, which corresponds to the sub-algebra $\mathfrak{sl}(2,C)_L^{(grav)}$. The connection $E = E^{am}\gamma_{am}$ corresponds to the non-diagonal components of the matrix A^{IJ}, described by the following way (see [5]): $E = e\varphi = e^a_\mu \gamma_a \varphi^m \gamma_m dx^\mu$. The connection $A_W = \frac{1}{2}A^{mn}\gamma_{mn}$ gives: $A_W = \frac{1}{2}A^i_W \tau_i$, which corresponds to the sub-algebra $\mathfrak{su}(2)_L$ of the weak interaction. Here τ_i are the Pauli matrices with $i = 1,2,3$.

Assuming that we have only scalar field $\varphi^m = (\varphi, \varphi^i)$, we can consider a symmetry breakdown of the Graviweakk Unification, leading to the following OW-action [4]:

$$I_{(OW)}\left(e, \varphi, A, A_W\right) = \frac{3}{8g_{uni}} \int_{\mathbf{M}} d^4x|e| \left(\frac{1}{16}|\varphi|^2 R - \frac{3}{32}|\varphi|^4\right.$$

$$\left. + \frac{1}{16} R_{ab}{}^{cd} R^{ab}{}_{cd} - \frac{1}{2}\mathcal{D}_a\varphi^\dagger \mathcal{D}^a\varphi - \frac{1}{4} F^i_{W\,ab} F^{i\ ab}_{W}\right). \tag{15}$$

In Eq. (15) we have the Riemann scalar curvature R; $|\varphi|^2 = \varphi^\dagger\varphi$ is a squared scalar field, which from the beginning is not the Higgs field of the Standard Model; $\mathcal{D}\varphi = d\varphi + [A_W, \varphi]$ is a covariant derivative of the scalar field, and $F_W = dA_W + [A_W, A_W]$ is a curvature of the gauge field A_W. The third term of the action (15) belongs to the Gauss-Bone theory of gravity (see for example Refs. [35, 36]).

Eq. (15) allows us to return to the GR formalism, when the dynamics is described by the metric tensor $g_{\mu\nu}$, and we have:

$$I_{(OW)}\left(\varphi, A, A_W\right) = \frac{3}{8g_{uni}} \int_{\mathbf{M}} d^4x\sqrt{-g} \left(\frac{1}{16}|\varphi|^2 R - \frac{3}{32}|\varphi|^4\right.$$

$$\left. + \frac{1}{16} R_{\alpha\beta\mu\nu} R^{\alpha\beta\mu\nu} - \frac{1}{2}\mathcal{D}_\mu\varphi^\dagger \mathcal{D}^\mu\varphi - \frac{1}{4} F^i_{W\,\mu\nu} F^{i\ \mu\nu}_{W}\right). \tag{16}$$

Here we consider the Jordan frame, in accordance with Ref. [5].

3.1 Existence of de Sitter solutions at the early time of the Universe

It is well-known that the early time acceleration era of the Universe is described by (quasi)-de Sitter solutions (see for example [37, 38]). So firstly it is important to investigate if de Sitter solutions exist in the case of the action (15). Such a problem was investigated by authors of Ref. [5]. Taking into account that our model [4] is a special case of the more general $SU(N)$ model [5] of the unification of gravity, gauge fields, and Higgs bosons, we can assume that the Universe is inherently de Sitter, where the 4-spacetime is a hyperboloid in a 5-dimensional Minkowski space under the constraint

$$-x_0^2 + x_1^2 + x_2^2 + x_3^2 + x_4^2 = r_{dS}^2, \tag{17}$$

where r_{dS} is the radius of curvature of the de Sitter space, or simply the de Sitter radius. The Hubble expansion of the Universe is then viewed as a process that approaches the asymptotic limit of a pure space which is de Sitter in nature, evidenced that the cosmological constant (CC) describes the dark energy (DE) substance, which has become dominant in the Universe at late times:

$$\Omega_{DE} = \rho_{DE}/\rho_{crit} \simeq 0.75, \tag{18}$$

where ρ is the energy density and the critical density is

$$\rho_{crit} = \frac{3H_0^2}{8\pi G_N} \simeq 1.88 \times 10^{-29} H_0^2, \tag{19}$$

where H_0 is the Hubble constant:

$$H_0 \simeq 1.5 \times 10^{-42}\ \text{GeV}. \tag{20}$$

Identifying the Einstein tensor as

$$G_{\mu\nu} = -\frac{3}{r_{dS}^2} g_{\mu\nu}, \tag{21}$$

we see that the only nontrivial component that satisfies this equation is a constant for the Ricci scalar:

$$R_0 = \frac{12}{r_{dS}^2}, \tag{22}$$

and

$$R_{\alpha\beta\mu\nu} R^{\alpha\beta\mu\nu} = \frac{1}{6} R_0^2 = \frac{24}{r_{dS}^4}. \tag{23}$$

As it was shown in Ref. [5], the nontrivial vacuum solution to the action (15) is de Sitter spacetime with a non-vanishing Higgs vacuum expectation value (VEV) of the scalar field: $v = \langle \varphi \rangle = \varphi_0$. The standard Higgs potential in Eq. (15) has an extremum at $\varphi_0^2 = R_0/3$ (with $R_0 > 0$), corresponding to a de Sitter spacetime background solution:

$$R_0 = \frac{12}{r_{dS}^2} = 3v^2 = 4\Lambda_0, \tag{24}$$

which implies vanishing curvature:

$$F_0 = \frac{1}{2} R_0 - \frac{1}{16} \Sigma_0 \varphi_0^2, \tag{25}$$

solving the field equations $\mathcal{D}F = dF + [A, F] = 0$, and strictly minimizing the action (15).

Based on this picture, the origin of the cosmological constant (and also DE) is associated with the inherent spacetime geometry, and not with vacuum energy of particles (we consider their contributions later). Note that as a fundamental constant under de Sitter symmetry, r_{dS} is not subject to quantum corrections.

Local dynamics then exist as fluctuations with respect to this cosmological background. In general, de Sitter space may be inherently unstable. The quantum instability of de Sitter space was investigated by various authors. Abbott and Deser [39] have shown that de Sitter space is stable under a restricted class of classical gravitational perturbations. So any instability of de Sitter space may likely have a quantum origin. Ref. [40] demonstrated through the expectation value of the energy-momentum tensor for a system with a quantum field in a de Sitter background space that in general it contains a term that is proportional to the metric tensor and grows in time. As a result, the curvature of the spacetime would decrease and de Sitter space tends to decay into the flat space (see similar conclusions in Ref. [41]). We note that the expectation value of such energy-momentum tensor is

$$\langle T_{\mu\nu} \rangle \propto g_{\mu\nu} H^4 (Ht), \tag{26}$$

where H is the Hubble parameter in the de Sitter metric, and

$$ds^2 = dt^2 - a^2(t) d\mathbf{x}^2 \tag{27}$$

with $a(t) = e^{Ht}$. According to (26), the decay time of this process is

$$\tau \sim H^{-1}. \tag{28}$$

In our case, this means that the decay time is of the order of the de Sitter radius:

$$\tau \sim r_{dS} \simeq 1.33 H_0^{-1}. \tag{29}$$

Since the age of our universe is smaller than r_{dS}, we are still observing the accelerating expansion in action.

Of course, we can consider the perturbation solutions of the de Sitter solution:

$$H(t) = H_{dS} + \Delta H(t), \tag{30}$$

where the perturbation is very small: $|\Delta H(t)| << 1$. The evolution of linear perturbation can behave as

$$\Delta H(t) = c + c_1 e^{\delta_1 t} + c_2 e^{\delta_2 t}, \tag{31}$$

(see for example Ref. [38]). But we don't concern this problem in this paper.

3.2 Parameters of Graviweak unification model

According to (15), the Newton gravitational constant G_N is defined by the expression:

$$8\pi G_N = (M_{Pl}^{(red.)})^{-2} = \frac{64 g_{uni}}{3v^2}, \tag{32}$$

a bare cosmological constant is equal to

$$\Lambda_0 = \frac{3}{4} v^2, \tag{33}$$

and

$$g_W^2 = 8 g_{uni}/3. \tag{34}$$

The coupling constant g_W is a bare coupling constant of the weak interaction, which also coincides with a value of the constant $g_2 = g_W$ at the Planck scale. Considering the running $\alpha_2^{-1}(\mu)$, where $\alpha_2 = g_2^2/4\pi$, we can carry out an extrapolation of this rate to the Planck scale, what leads to the following estimation [42, 43]:

$$\alpha_2(M_{Pl}) \sim 1/50, \tag{35}$$

and then the overall GWU parameter is: $g_{uni} \sim 0.1$.

According to Eqs. (16) and (32), we obtain the following GWU action:

$$\begin{aligned} I_{(OW)}\left(\varphi, A, A_W\right) = \int_{\mathbf{M}} d^4x \sqrt{-g} \Big[\left(\frac{M_{Pl}^{red}}{v}\right)^2 \left(\frac{1}{2}|\varphi|^2 R - \frac{3}{4}|\varphi|^4 + \frac{1}{2} R_{\alpha\beta\mu\nu} R^{\alpha\beta\mu\nu}\right) \\ - \frac{1}{g_W^2}\left(\frac{1}{2}\mathcal{D}_\mu \varphi^\dagger \mathcal{D}^\mu \varphi + \frac{1}{4} F^i_{W\mu\nu} F_W^{i\ \mu\nu}\right) \Big]. \end{aligned} \tag{36}$$

In the action (36) the Lagrangian includes the non-minimal coupling with gravity [9–20]. We see that the field φ is not stuck at φ_0 anymore, but it can be represented as

$$\varphi = \varphi_0 - \sigma = v - \sigma, \tag{37}$$

where the real scalar field σ is an <u>inflaton</u>. Here we see that in the minimum, when $\varphi = v$, the inflaton field is zero ($\sigma = 0$), and then increases with the falling of the field φ.

Inserting designations (37) into the action (36), we obtain:

$$\begin{aligned} I_{(OW)}\left(\varphi, A, A_W\right) = \int_{\mathbf{M}} d^4x \sqrt{-g} \Big[\left(\frac{M_{Pl}^{red}}{v}\right)^2 \left(\frac{1}{2}(v-\sigma)^2 R - \frac{3}{4}(v-\sigma)^4 + \frac{1}{2} R_{\alpha\beta\mu\nu} R^{\alpha\beta\mu\nu}\right) \\ - \frac{1}{g_W^2}\left(\frac{1}{2}\mathcal{D}_\mu (v-\sigma) \mathcal{D}^\mu (v-\sigma) + \frac{1}{4} F^i_{W\mu\nu} F_W^{i\ \mu\nu}\right) \Big], \end{aligned} \tag{38}$$

or (in a suitable gauge condition):

$$I_{(OW)}\left(\varphi, A, A_W\right) = \int_{\mathbf{M}} d^4x\sqrt{-g}\big[\left(M_{Pl}^{red}\right)^2\left(\frac{1}{2}(1-\frac{\sigma}{v})^2R - \Lambda_0(1-\frac{\sigma}{v})^4 + \frac{1}{2v^2}R_{\alpha\beta\mu\nu}R^{\alpha\beta\mu\nu}\right)$$

$$- \frac{1}{g_W^2}\left(\frac{1}{2}\mathcal{D}_\mu\sigma\mathcal{D}^\mu\sigma + \frac{1}{4}F^i_{W\,\mu\nu}F_W^{i\ \mu\nu}\right)\big], \tag{39}$$

Considering the expansion in powers of small values of σ/v, and leaving only the first-power terms, we can present the following gravitational part of the action near the Planck scale:

$$I_{(grav\ OW)} = \int_M d^4x\sqrt{-g}\big[\left(M_{Pl}^{red}\right)^2\left(\frac{1}{2}R - \Lambda_0 - (R-4\Lambda_0)\frac{\sigma}{v} + (\frac{R}{2} - 6\Lambda_0)\frac{\sigma^2}{v^2} + ...\right)$$

$$- \frac{1}{2g_W^2}\mathcal{D}_\mu\sigma\mathcal{D}^\mu\sigma + ...\big]. \tag{40}$$

As it was shown in Subsection 3.1, near the minimum at the Planck scale we have:

$$R = R_0 + \Delta R,$$

where $\Delta R << R_0$. Here $\Lambda_0 = \frac{3}{4}v^2 = R_0/4$. Using the last relations, we can neglect the third term in Eq. (40), i.e $\Delta R\sigma/v$, and obtain:

$$I_{(grav\ OW)} = \int_M d^4x\sqrt{-g}\left(M_{Pl}^{red}\right)^2\left(\frac{1}{2}(1+\frac{\sigma^2}{v^2})R - \Lambda_0 - \frac{6\Lambda_0}{v^2}\sigma^2 + ...\right)$$

$$- \frac{1}{2g_W^2}\mathcal{D}_\mu\sigma\mathcal{D}^\mu\sigma + ...\big]. \tag{41}$$

Now it is possible to get rid of the non-minimal coupling to gravity by making the conformal transformation from the Jordan frame of Eq. (41) to the Einstein frame (see Refs. [9,19]).

According to Refs. [9,19], in units $M_{Pl}^{red} = 1$, the Lagrangian including the generalized non-minimal coupling to gravity reads:

$$L_J = \sqrt{-g}\left(\frac{1}{2}\Omega(\chi)R - \Lambda_0 - \frac{1}{2}(\partial\chi)^2 - V_J(\chi) + ...\right), \tag{42}$$

where

$$\Omega = 1 + \xi\chi^2. \tag{43}$$

In our case:

$$\chi = \frac{\sigma}{g_W}, \tag{44}$$

and

$$\xi = \frac{g_W^2}{v^2} = \frac{1}{8}, \tag{45}$$

and

$$V_J(\chi) = \frac{1}{2}m^2\chi^2, \tag{46}$$

where

$$m^2 = \frac{9}{8}v^2 \tag{47}$$

is a bare mass of the inflaton.

In order to transform from the Jordan frame to the canonical Einstein frame, we need to redefine the metric:

$$\hat{g}_{\mu\nu} = \Omega g_{\mu\nu}. \tag{48}$$

Finally, the Larangian in the Einstein frame has the form:

$$L_E = \sqrt{-\hat{g}}\left(\frac{1}{2}\hat{R} - \Lambda_0 - \frac{1}{2}(\partial\chi)^2 - V_E(\chi) + ...\right), \tag{49}$$

where

$$V_E(\chi) = \frac{V_J(\chi)}{\Omega^2(\chi)}.$$

In our case we have small values of the field χ, $\Omega \simeq 1$ (see [9]), and in the Einstein frame our action (41) near the Planck scale minimum is

$$I^{(E)}_{(grav\ OW)} \simeq \int_M d^4x\sqrt{-g}\big[\left(M^{red}_{Pl}\right)^2\left(\frac{1}{2}R - \Lambda_0 - \frac{1}{2}m^2\chi^2 + \frac{1}{2v^2}R_{\alpha\beta\mu\nu}R^{\alpha\beta\mu\nu}\right)$$
$$- \frac{1}{2}\mathcal{D}_\mu\chi\mathcal{D}^\mu\chi - \frac{1}{4g_W^2}F^i_{W\,\mu\nu}F_W^{i\ \mu\nu}\big]. \tag{50}$$

4 Multiple Point Model

The radiative corrections to the effective Higgs potential, considered in Refs. [45,46], bring to the emergence of the second minimum of the effective Higgs potential at the Planck scale. It was shown that in the 2-loop approximation of the effective Higgs potential, experimental values of all running coupling constants in the SM predict an existence of the second minimum of this potential located near the Planck scale, at the value $v_2 = \varphi_{min2} \sim M_{Pl}$.

In general, a quantum field theory allows an existence of several minima of the effective potential, which is a function of a scalar field. If all vacua, corresponding to these minima, are degenerate, having zero cosmological constants, then we can speak about the existence of a multiple critical point (MCP) at the phase diagram of theory considered for the investigation (see Refs. [44, 47]). In Ref. [44] Bennett and Nielsen suggested the Multiple Point Model (MPM) of the Universe, which contains simply the SM itself up to the scale $\sim 10^{18}$ GeV. In Ref. [48] the MPM was applied (by the consideration of the two degenerate vacua in the SM) for the prediction of the top-quark and Higgs boson masses, which gave:

$$M_t = 173 \pm 5 \text{ GeV}, \qquad M_H = 135 \pm 9 \text{ GeV}. \tag{51}$$

Later, the prediction for the mass of the Higgs boson was improved by the calculation of the two-loop radiative corrections to the effective Higgs potential [45,46]. The predictions: 125 GeV $\lesssim M_H \lesssim$ 143 GeV in Ref. [45], and 129 $\pm$ 2 GeV in Ref. [46] – provided the possibility of the theoretical explanation of the value $M_H \approx 126$ GeV observed at the LHC. The authors of Ref. [49] have shown that the most interesting aspect of the measured value of M_H is its near-criticality. They have thoroughly studied the condition of near-criticality in terms of the SM parameters at the high (Planck) scale. They extrapolated the SM parameters up to large energies with full 3-loop NNLO RGE precision. All these results mean that the radiative corrections to the Higgs effective potential lead to the value of the Higgs mass existing in the Nature.

The behavior of the Higgs self-coupling λ is quite peculiar: it decreases with energy to eventually arrive to a minimum at the Planck scale values and then starts to increase there after. Within the experimental and theoretical uncertainties the Higgs coupling λ

may stay positive all way up till the Planck scale, but it may also cross zero at some scale μ_0. If that happens, our Universe becomes unstable.

The largest uncertainty in couplings comes from the determination of the top Yukawa coupling. Smaller uncertainties are associated to the determination of the Higgs boson mass and the QCD coupling α_s (see Refs. [45, 46, 49]).

Calculations of the lifetime of the SM vacuum are extremely sensitive to the Planck scale physics. The authors of Refs. [50–52] showed that if the SM is valid up to the Planck scale, then the Higgs potential becomes unstable at $\sim 10^{11}$ GeV. There are two reasons of this instability. In typical tunnelling calculations, the value of the field at the center of the critical bubble is much larger than the point of the instability. In the SM case, this turns out to be numerically within an order of magnitude of the Planck scale.

The measurements of the Higgs mass and top Yukawa coupling indicate that we live in a very special Universe: at the edge of the absolute stability of the EW vacuum. If fully stable, the SM can be extended all the way up to the inflationary scale and the Higgs field, non-minimally coupled to gravity with strength ξ, can be responsible for the inflation (see Ref. [9]).

Having substituted in Eq.(32) the values of $g_{uni} \simeq 0.1$ and $G_N = 1/8\pi(M_{Pl}^{red.})^2$, where $M_{Pl}^{red.} \approx 2.43 \cdot 10^{18}$ GeV, it is easy to obtain the VEV's value v, which in this case is located near the Planck scale:

$$v = v_2 \approx 3.5 \cdot 10^{18}\mathrm{GeV}. \tag{52}$$

Such a result takes place, if the Universe at the early stage stayed in the "false vacuum", in which the VEV of the Higgs field is huge: $v = v_2 \sim 10^{18} GeV$. The exit from this state could be carried out only by means of the existence of the second scalar field. In the present paper we assume that the second scalar field, participating into the Inflation, is the mirror Higgs field, which arises from the interaction between the Higgs fields of the visible and invisible sectors of the Universe.

5 Mirror world with broken mirror parity

As it was noted at the beginning of this paper, we assumed the parallel existence in the Nature of the visible (OW) and invisible (MW) (mirror) worlds.

Such a hypothesis was suggested in Refs. [53, 54].

The Mirror World (MW) is a mirror copy of the Ordinary World (OW) and contains the same particles and types of interactions as our visible world, but with the opposite chirality. Lee and Yang [53] were first to suggest such a duplication of the worlds, which restores the left-right symmetry of the Nature. The term "Mirror Matter" was introduced by Kobzarev, Okun and Pomeranchuk [54], who first suggested to consider MW as a hidden (invisible) sector of the Universe, which interacts with the ordinary (visible) world only via gravity, or another (presumably scalar) very weak interaction.

In the present paper we consider the hidden sector of the Universe as a Mirror World (MW) with broken Mirror Parity (MP) [55–59]. If the ordinary and mirror worlds are identical, then O- and M-particles should have the same cosmological densities. But this is immediately in conflict with recent astrophysical measurements [60–62]. Astrophysical and cosmological observations have revealed the existence of the Dark Matter (DM), which constitutes about 25% of the total energy density of the Universe. This is five times larger than all the visible matter, $\Omega_{DM} : \Omega_M \simeq 5 : 1$. Mirror particles have been suggested as candidates for the inferred dark matter in the Universe [58, 63, 64] (see also [65]). Therefore, the mirror parity (MP) is not conserved, and the OW and MW are not identical.

The group of symmetry G_{SM} of the Standard Model was enlarged to $G_{SM} \times G'_{SM'}$, where G_{SM} stands for the observable SM, while $G'_{SM'}$ is its mirror gauge counterpart. Here O(M)- particles are singlets of the group $G'_{SM'}$ (G_{SM}).

It was assumed that the VEVs of the Higgs doublets ϕ and ϕ' are not equal [55–59]:

$$\langle\phi\rangle = v, \quad \langle\phi'\rangle = v', \quad \text{and} \quad v \neq v'.$$

The parameter characterizing the violation of the MP is $\zeta = v'/v \gg 1$. Astrophysical estimates give: $\zeta > 30, \quad \zeta \sim 100$ (see Refs. [66,67] and references there).

The action $I_{(MW)}$ in the mirror world is represented by the same integral (15), in which we have to make the replacement of all OW-fields by their mirror counterparts: $e, \varphi, A, A_W, R \to e', \varphi', A', A'_W, R'$.

In general, ordinary and mirror matters interact with gravity by two separate metric tensors $g^L_{\mu\nu}$ and $g^R_{\mu\nu}$, i.e. each sector of the Universe has its own GR-like gravity.

In this investigation we assume (see [68] and [69]) that the left-handed gravity coincides with the right-handed gravity: the left-handed and right-handed connections are equal: $A' = A$, i.e. $A^L = A^R$. In this case $g^L_{\mu\nu} = g^R_{\mu\nu}$, and the left-handed and right-handed gravity equally interact with visible and mirror matters.

Then in the Einstein frame, the MW-action near the Planck scale minimum is

$$I^{(E)}_{(grav\ MW)} \simeq \int_M d^4x\sqrt{-g}\big[\,\big(M^{red}_{Pl}\big)^2\left(\frac{1}{2}R' - \Lambda'_0 - \frac{1}{2}m'^2\chi'^2 + \frac{1}{2v'^2}R'_{\alpha\beta\mu\nu}R'^{\alpha\beta\mu\nu}\right)$$
$$- \frac{1}{2}\mathcal{D}_\mu\chi'\mathcal{D}^\mu\chi' - \frac{1}{4g'^2_W}F'^i_{W\,\mu\nu}F'^{i\ \mu\nu}_{W}\big]. \tag{53}$$

¿From Eq. (53), it is not difficult to determine that in the hidden (mirror) world the Newton gravitational constant G'_N is defined by the expression:

$$8\pi G'_N = (M'^{(red.)}_{Pl})^{-2} = \frac{64g'_{uni}}{3v'^2}, \tag{54}$$

a bare cosmological constant is equal to

$$\Lambda'_0 = \frac{3}{4}v'^2, \tag{55}$$

and

$$g'^2_W = 8g'_{uni}/3. \tag{56}$$

If we assume the same gravity in the OW and MW, then we have:

$$G'_N = G_N, \quad M'^{(red.)}_{Pl} = M^{(red.)}_{Pl}, \tag{57}$$

what means that

$$\frac{g'_{uni}}{v'^2} = \frac{g_{uni}}{v^2}, \tag{58}$$

$$g'_{uni} \neq g_{uni}, \quad g'_W \neq g_W. \tag{59}$$

Then:

$$g'^2_W = \frac{v'^2}{v^2}g^2_W = \zeta^2 g^2_W, \tag{60}$$

and

$$\Lambda'_0 = \zeta^2\Lambda_0. \tag{61}$$

It is well-known that the hidden (invisible) sector of the Universe interacts with the ordinary (visible) world only via gravity, or another very weak interaction (see for example

[54, 64, 70]). In particular, the authors of Ref. [71] assumed, that along with gravitational interaction there also exists the interaction between the initial Higgs fields of both OW- and MW-worlds:

$$V_{int} = \alpha_\chi(\chi^\dagger\chi)(\chi'^\dagger\chi'). \tag{62}$$

Taking into account the interaction (62) and OW- and MW- actions (50), (53), we obtain the total action of the Universe (in the Einstein frame):

$$I^{(E)}_{(tot)} \simeq \int_M d^4x\sqrt{-g}\big[\left(M_{Pl}^{red}\right)^2\left(\frac{1}{2}(R+R') - (\Lambda_0+\Lambda_0') - \frac{1}{2}(m^2\chi^2 + m'^2\chi'^2) - \alpha_\chi(\chi^2)(\chi'^2)\right)$$
$$+\frac{1}{16}\left(\frac{1}{g_W^2}R_{\alpha\beta\mu\nu}R^{\alpha\beta\mu\nu} + \frac{1}{g'^2_W}R'_{\alpha\beta\mu\nu}R'^{\alpha\beta\mu\nu}\right)$$
$$-\frac{1}{2}\mathcal{D}_\mu\chi\mathcal{D}^\mu\chi - \frac{1}{2}\mathcal{D}'_\mu\chi'\mathcal{D}'^\mu\chi' - \frac{1}{4g_W^2}F^i_{W\mu\nu}F^{i\ \mu\nu}_W - \frac{1}{4g'^2_W}F'^i_{W\mu\nu}F'^{i\ \mu\nu}_W + L_{SM} + L'_{SM'}\big], \tag{63}$$

where L_{SM} and $L'_{SM'}$ are the SM and SM' matter Lagrangians, respectively.

6 Cosmological constant problem

In the Einstein-Hilbert action the vacuum energy is:

$$\rho_{vac} = \left(M_{Pl}^{red}\right)^2\Lambda, \tag{64}$$

where Λ is the cosmological constant of the Universe.

In our case, given by Eq. (63), the vacuum energy density is

$$\rho_0 = \left(M_{Pl}^{red}\right)^2(\Lambda_0+\Lambda_0') = \left(M_{Pl}^{red}\right)^2(1+\zeta^2)\Lambda_0. \tag{65}$$

However, assuming the existence of the discrete spacetime of the Universe at the Planck scale and using the prediction of the non-commutativity suggested by B.G. Sidharth [6, 7], we obtain that the gravitational part of the GWU action has the vacuum energy density equal to zero, or almost zero.

Indeed, the total cosmological constant and the total vacuum density of the Universe contain also the vacuum fluctuations of fermions and other SM boson fields:

$$\Lambda \equiv \Lambda_{eff} = \Lambda^{ZMD} + (\Lambda_0+\Lambda_0') - \Lambda_s^{(NC)} + \Lambda_f^{(NC)}, \tag{66}$$

where Λ^{ZMD} is zero mode degrees of freedom of all fields existing in the Universe, and $\Lambda_{s,f}^{(NC)}$ are boson and fermion contributions of the non-commutative geometry of the discrete spacetime at the Planck scale. If according to the theory by B.G. Sidharth [6, 7], we have:

$$\rho_{vac}^{(0)} = \left(M_{Pl}^{red}\right)^2\Lambda^{(0)} = \left(M_{Pl}^{red}\right)^2\left(\Lambda^{ZMD} + (\Lambda_0+\Lambda_0') - \Lambda_s^{(NC)}\right) \approx 0, \tag{67}$$

then Eq. (63) contains the cosmological constant $\Lambda^{(0)} \approx 0$. In Eqs. (66) and (67) the bosonic (scalar) contribution of the non-commutativity is:

$$\rho^{(NC)}_{(scalar)} \simeq m_s^4 \quad (\text{in units}:\ \hbar = c = 1), \tag{68}$$

which is given by the mass m_s of the primordial scalar field φ. Then the discrete spacetime at the very small distances is a lattice (or has a lattice-like structure) with a parameter $a = \lambda_s = 1/m_s$. This is a scalar length:

$$a = \lambda_s \sim 10^{-19}\ \text{GeV}^{-1},$$

which coincides with the Planck length: $\lambda_{Pl} = 1/M_{Pl} \approx 10^{-19}$ GeV^{-1}. The assumption:

$$\Lambda^{(0)} = \Lambda^{ZMD} + (\Lambda_0 + \Lambda'_0) - \Lambda_s^{(NC)} \approx 0 \tag{69}$$

means that the Graviweak Unification model contains the cosmological constant equal to zero, or almost zero.

B.G. Sidharth gave in Ref. [8] the estimation:

$$\rho_{DE} = \left(M_{Pl}^{red}\right)^2 \Lambda_f^{(NC)}, \tag{70}$$

considering the non-commutative contribution of light primordial neutrinos as a dominant contribution to ρ_{DE}, which coincides with astrophysical measurements [60–62]:

$$\rho_{DE} \approx (2.3 \times 10^{-3}\ \text{eV})^4. \tag{71}$$

Returning to the inflation model, we rewrite the action (63) as:

$$I_{(tot)} = \int_M d^4x\sqrt{-g}\left[\left(M_{Pl}^{red}\right)^2\left(\frac{1}{2}(R+R') - \Lambda - \frac{m^2}{2}\chi^2 - \frac{m'^2}{2}\chi'^2 - \alpha_\chi(\chi^2)(\chi'^2)\right) + ...\right], \tag{72}$$

where the positive cosmological constant Λ is not zero, but is very small.

7 Inflation from the Higgs Field False Vacuum

Inflation from a local minimum is a viable scenario of the hybrid model by A. Linde [28] provided a graceful exit to the radiation-dominated era, which can be obtained via some mechanism beyond the SM. It was shown in Refs. [1] and [23, 24] that this mechanism is consistent only with a narrow range of values of the Higgs boson mass, indicated experimentally by ATLAS and CMS [26, 27], and also depends on a narrow range of the top-quark mass values.

The existence of the second Higgs field χ' could be the cause of the hybrid inflation (see [28]), bringing the Universe out of the "false vacuum" with the VEV $v_2 \sim 10^{18}$ GeV. This circumstance provided the subsequent transition to the vacuum with the Higgs VEV v_1 existing at the Electroweak (EW) scale. Here $v_1 \approx 246$ GeV is a vacuum, in which we live at the present time.

Using the action (72), given by GWU, we obtain near the local "false vacuum" the following gravitational potential in units $M_{Pl}^{red} = 1$:

$$V(\chi, \chi') = \Lambda + \frac{m^2}{2}\chi^2 + \frac{m'^2}{2}\chi'^2 + \alpha_\chi(\chi^2)(\chi'^2). \tag{73}$$

The local minimum of the potential (73) at $\varphi = v$ (when $\chi = 0$) and ${\varphi'}_0 \neq v'$ ($\chi' \neq 0$), gives:

$$V(0,\ \chi') = \Lambda + \frac{m'^2}{2}(\chi')^2. \tag{74}$$

The last equation (74) shows that the potential $V(0, \chi')$ grows with growth of χ', i.e. with falling of the field φ'. It means that a barrier of potential grows and at some value $\chi' = \chi'_{in}$ the Higgs field φ' begins its inflationary falling.

The local minimum at $\chi = 0$ and $\chi' = \chi'|_{in}$ is given by the following condition:

$$\frac{\partial V(\chi, \chi')}{\partial \chi^2}\Big|_{\chi=0} = \frac{m^2}{2} + \alpha_\chi {\chi'}^2_{in} = 0, \tag{75}$$

and

$$\frac{\partial V(\chi,\chi')}{\partial \chi'^2}\Big|_{\chi'=0} = \frac{m'^2}{2} + \alpha_\chi \chi_{in}^2 = 0, \tag{76}$$

what gives:

$$\chi_{in}^2 = -\frac{m'^2}{2\alpha_\chi} \quad \text{and} \quad \chi'^2_{in} = -\frac{m^2}{2\alpha_\chi}. \tag{77}$$

If $\alpha_\chi < 0$, we have the following value of the barrier of potential, at which the inflationary falling of the Higgs field φ' begins:

$$V(0,\chi'|_{in}) = \Lambda + \frac{(mm')^2}{4|\alpha_\chi|}, \tag{78}$$

and according to Eq. (47), we have:

$$V(0,\chi'|_{in}) = \Lambda + \frac{81(vv')^2}{256|\alpha_\chi|}. \tag{79}$$

7.1 Inflation with the Higgs doublets of the SM and SM'

Our next step is an assumption that during the inflation the scalar field χ, which is the SM-triplet, decays into the two Higgs doublets of the SM:

$$\chi \to \phi^\dagger + \phi. \tag{80}$$

As a result, we have:

$$\chi = a_d|\phi|^2, \tag{81}$$

where ϕ is the Higgs doublet field of the Standard Model. The Higgs field ϕ also interacts directly with the mirror Higgs field ϕ', according to the assumption of Ref. [71]:

$$V_{int} = \alpha_\phi(\phi^\dagger\phi)(\phi'^\dagger\phi'). \tag{82}$$

The Higgs field ϕ' has a time of the evolution and modifies the shape of the barrier, so that at some value ϕ'_E, it can roll down the field ϕ. This possibility, which we consider in this paper, is given by the so-called Hybrid inflation scenario by A. Linde [28]. Here we assume that the field ϕ begins the inflation at the value $\phi|_{in} \simeq H_0$, where H_0 is the Hubble rate (this is a result of Refs. [6, 7]).

Using the action (72), given by GWU, we obtain near the local "false vacuum" the following gravitational potential in units $M_{Pl}^{red} = 1$:

$$V(\phi,\ \phi') \simeq \Lambda + \frac{\lambda}{4}|\phi|^4 + \frac{\lambda'}{4}|\phi'|^4 + \frac{a_\phi}{4}|\phi|^2|\phi'|^2, \tag{83}$$

where $\lambda = 12a_d^2m^2$ and $\lambda' = 12{a'_d}^2{m'}^2$ are self-couplings of the Higgs doublet fields ϕ and ϕ', respectively.

In the present investigation we considered only the results of such an inflation, which corresponds to the assumption of the MPP, that cosmological constant is zero (or almost zero) at both vacua: at the "first vacuum" with the VEV $v_1 = 246$ GeV and at the "second vacuum" with the VEV $v = v_2 \sim 10^{18}$ GeV. If so, we have the following conditions of the MPP (see section 4):

$$V_{eff}(\phi_{min1}) = V_{eff}(\phi_{min2}) = 0, \tag{84}$$

$$\frac{\partial V_{eff}}{\partial|\phi|^2}\Big|_{\phi=\phi_{min1}} = \frac{\partial V_{eff}}{\partial|\phi|^2}\Big|_{\phi=\phi_{min2}} = 0. \tag{85}$$

Being far from the Planck scale, we can present the following expression for the low energy total effective Higgs potential:

$$V_{eff} = -\frac{\mu^2}{2}|\phi|^2 + \frac{1}{4}\lambda(\phi)|\phi|^4 - \frac{\mu'^2}{2}|\phi'|^2 + \frac{1}{4}\lambda'(\phi')|\phi'|^4 + \frac{1}{4}\alpha_\phi(\phi,\phi')|\phi|^2|\phi'|^2, \qquad (86)$$

where $\alpha_\phi(\phi,\phi')$ is a coupling for the interaction of the ordinary Higgs field ϕ with the mirror Higgs field ϕ'. In Eq. (86) the Higgs fields have tachyonic masses μ, μ', as usual.

According to the MPP, at the critical point of the phase diagram of our theory, corresponding to the "second vacuum", we have:

$$\mu = \mu' \simeq 0, \quad \lambda(\phi_0) \simeq 0, \quad \lambda'(\phi'_0) \simeq 0, \qquad (87)$$

and then

$$\alpha_\phi(\phi_0, \phi'_0) \simeq 0, \quad \text{if} \quad V^{crit}_{eff}(v_2) \simeq 0. \qquad (88)$$

At the critical point, corresponding to the first EW vacuum with the VEV $v_1 = 246$ GeV, we also have $V^{crit}_{eff}(v_1) \simeq 0$, according to the MPP prediction of the existence of almost degenerate vacua in the Universe. Then the tree-level Higgs potential near vacua is

$$V(\phi,\phi') = -\frac{\mu^2}{2}|\phi|^2 + \frac{1}{4}\lambda|\phi|^4 - \frac{\mu'^2}{2}|\phi'|^2 + \frac{1}{4}\lambda'|\phi'|^4 + \frac{1}{4}\alpha_\phi|\phi|^2|\phi'|^2 + CC, \qquad (89)$$

where CC is a constant, depending on the vacuum values of the potential.

If $V(v_1, v'_1) = 0$, then CC (providing zero cosmological constant) is:

$$CC = \frac{1}{4}\alpha_\phi(v_1 v'_1)^2, \qquad (90)$$

and we can present the tree-level Higgs potential by the following expression:

$$V(\phi,\phi') = \frac{1}{4}\left(\lambda(|\phi|^2 - v_1^2)^2 + \lambda'(|\phi'|^2 - v'^2_1)^2 + \alpha_\phi(|\phi'|^2 - v'^2_1)(|\phi|^2 - v_1^2)\right), \qquad (91)$$

where in Eq. (89) we have:

$$\mu^2 = \lambda v_1^2 + \frac{1}{2}\alpha_\phi {v'_1}^2 \quad \text{and} \quad \mu'^2 = \lambda' {v'_1}^2 + \frac{1}{2}\alpha_\phi {v_1}^2. \qquad (92)$$

If $\alpha_\phi = 0$, then we see from Eqs. (90) that:

$$CC = 0, \qquad (93)$$

and the MPP-conditions (87) take place.

Eqs. (91) determines VEVs:

$$v_1^2 = 2\frac{\alpha_\phi \mu'^2 - 2\mu^2\lambda'}{\alpha_\phi^2 - 4\lambda\lambda'} \quad \text{and} \quad {v'_1}^2 = 2\frac{\alpha_\phi \mu^2 - 2\mu'^2\lambda}{\alpha_\phi^2 - 4\lambda\lambda'}. \qquad (94)$$

If $\alpha_\phi = 0$, then:

$$v_1^2 = \frac{\mu^2}{\lambda} \quad \text{and} \quad {v'_1}^2 = \frac{\mu'^2}{\lambda'}, \qquad (95)$$

and we have well-known relations for the usual Higgs model.

The potential (91) vanishes, when $\phi' = \phi'_0 = v'_1$ and $\phi = \phi_0 = v_1$, recovering the ordinary or mirror Standard Model, respectively.

At the end of inflation we have: $\phi' = {\phi'}_E$, and the first vacuum value of the potential V is:

$$V(v_1, {\phi'}_E) = \frac{1}{4}\lambda'({\phi'}_E)({\phi'}_E|^2 - {v'}_1^2)^2, \tag{96}$$

and

$$\frac{\partial V}{\partial|\phi|^2}\left|\begin{array}{c} \phi = v_1 \\ \phi' = {\phi'}_E \end{array}\right| = 0. \tag{97}$$

This means that the end of inflation is given by the value:

$$\phi'_{end} = {\phi'}_E = v'_1 = \zeta v_1, \tag{98}$$

which coincides with the VEV $< \phi' >= v'_1$ of the field ϕ' at the first vacuum in the mirror world MW. Thus:

$$V(\phi, {\phi'}_E) = \frac{1}{4}\lambda(|\phi|^2 - v_1^2)^2, \tag{99}$$

recovering the Standard Model with the first vacuum VEV $v_1 \approx 246$ GeV.

7.2 The calculation of the number of e-folds

In this section we try to estimate the number of e-folds in our model with two scalar fields, φ and φ'. Here we follow the calculations given by Ref. [20].

Near the Planck scale the tree-level Higgs potential is given by

$$V = \frac{\lambda'}{4}(s^2 - v'^2)^2 + \frac{\lambda}{4}(h^2 - v^2)^2 + \frac{\alpha_h}{4}(s^2 - v'^2)(h^2 - v^2), \tag{100}$$

where $s = |\varphi'|$ and $h = |\varphi|$. In Eq. (100) $s_0 = v'$ and $h_0 = v$ are VEVs of the Planck scale vacua ("false vacua").

During inflation the mirror field s rolls towards its minimum $< s >$ and the mixing term between h and s will grow and lift the false vacuum. The end of inflation is given by the point, at which the false minimum disappears. Here we have a situation similar to the hybrid potential by A. Linde [28], in which the rolling of s triggers the waterfall field h. Then:

$$\frac{\partial V}{\partial s^2}|_{s=<s>,h=<h>} = 0, \tag{101}$$

what gives:

$$< s >^2 -v'^2 + \frac{\alpha_h}{2\lambda'}(< h >^2 -v^2) = 0, \tag{102}$$

and we have the following minimum of the tachyonic field s:

$$< s >^2= v'^2 - \frac{\alpha_h}{2\lambda'}(< h >^2 -v^2). \tag{103}$$

According to (76), using (37), (44), (45) and (47), we obtain:

$$< h >^2= |v - \sigma_{in}|^2 = |v - g_W\chi_{in}|^2 = |v - \frac{3}{8}\frac{vv'}{\sqrt{2\alpha}}|^2, \tag{104}$$

where $\alpha \equiv |\alpha_h|$ (Eqs. (76)-(79) tell us that $\alpha_h < 0$). Then the renormalized potential can be written as a function of s (compare with Ref. [20]):

$$V_s = \frac{\lambda'}{4}(s^2- < s >^2)^2 + \frac{1}{4}(\lambda_{eff} - \frac{{\alpha_h}^2}{2\lambda'})(< h >^2 -v^2)^2. \tag{105}$$

Here we neglected the h^2 term. In Eq. (105) the value $\lambda_{eff} \simeq 0.129$ is inferred from the Higgs mass measurements (see Ref. [20]), and

$$< s >^2 = \frac{1}{2\lambda'}\left(M_h'^2 - \alpha_h(< h >^2 - v^2)\right) = v'^2 + \frac{\alpha}{2\lambda'}(< h >^2 - v^2), \tag{106}$$

where the mirror Higgs boson mass is given by the relation $M_h'^2 = 2\lambda' v'^2$.

Using Eq. (104), we have:

$$< h >^2 - v^2 = \frac{\zeta v^3}{\alpha}\left(\frac{9}{128}\zeta v - \frac{3}{4}\sqrt{\frac{\alpha}{2}}\right). \tag{107}$$

When the inflation begins, the "false vacua" disappear:

$$< h >^2 = 0 \quad \text{and} \quad < s >^2 = 0. \tag{108}$$

¿From Eq. (104) the condition $< h >^2 = 0$ (see Eq. (108)) determines the value α (equal to α_0) at the beginning of inflation:

$$\alpha_0 \simeq \frac{9}{128}\zeta^2 v^2. \tag{109}$$

Eqs. (106) and (108) give:

$$< s >^2 = \zeta^2 v^2 - \frac{\alpha}{2\lambda'} v^2 = 0, \tag{110}$$

and we obtain the following result:

$$\alpha_0 = 2\lambda' \zeta^2. \tag{111}$$

Then, according to Eqs. (109) and (111), we have:

$$\lambda' = \frac{9}{256} v^2. \tag{112}$$

Taking into account the relations (105), (106) and (107), we obtain:

$$V_s = As^4 + Bs^2 + C, \tag{113}$$

where

$$A = \frac{1}{4}\lambda',$$
$$B = -\frac{1}{2}\lambda' < s >^2,$$
$$C = \frac{1}{4}\lambda' < s >^4 + \frac{9}{512\alpha}(0.129 - \frac{\alpha^2}{2\lambda'})\zeta^2 v^4. \tag{114}$$

In cosmology the total number of e-folds in units $M_{Pl}^{red} = 1$ (where $M_{Pl}^{red} \simeq 2.43 \cdot 10^{18}$ GeV) is given by:

$$N^* = \int_{t_{in}}^{t_{end}} H_0 dt, \tag{115}$$

what means (see Ref. [20]):

$$N^* = \int_{s_{in}}^{s_{end}} \frac{V_s}{V_s'} ds, \tag{116}$$

where s_{in} and s_{end} are initial and end values of s during inflation. The calculations give:

$$s_{in} = |\varphi'_{in}| = |v' - \sigma'_{in}| = |v' - g'_w \chi'_{in}| = |v' - \frac{mv'}{4\sqrt{\alpha}}| = \zeta v |1 - \frac{3}{8}\frac{v}{\sqrt{2\alpha}}|, \tag{117}$$

and, according to relations (37), (44), (45), (47), (81) and (98):

$$s_{end} = |\varphi'_{end}| = |v' - \sigma'_{end}| = |v' - g'_w \chi'_{end}| = |v' - g'_W a'_d |\phi'_{end}|^2|$$

$$= |v' - \frac{1}{6}\sqrt{\lambda'/3}|\phi'_{end}|^2| = |v' - \frac{1}{6}\sqrt{\lambda'/3}(\zeta v_1)^2|, \tag{118}$$

or

$$s_{end} \simeq v' = \zeta v. \tag{119}$$

In Eq. (116) we have:

$$V'_s = \frac{\partial V_s}{\partial s} = 2s\frac{\partial V_s}{\partial s^2}. \tag{120}$$

The model developed in the present paper gives (see Eq. (113)):

$$N^* = \frac{1}{4}\int_{s_{in}^2}^{s_{end}^2} \frac{(As^4 + Bs^2 + C)}{s^2(2As^2 + B)} ds^2. \tag{121}$$

Now we can obtain from Eqs. (114) the following estimations of coefficients A, B, C:

$$A = \frac{\lambda'}{4}, \quad B = -\frac{\lambda'}{2}a^2, \quad \text{and} \quad C = \frac{\lambda'}{4}a^4 + \frac{9}{512\alpha}(0.129 - \frac{\alpha^2}{2\lambda'})\zeta^2 v^4, \tag{122}$$

where

$$a^2 =< s >^2 . \tag{123}$$

Finally, we obtain the following result:

$$N^* = \frac{1}{8}\left(x_{end} - x_{in}\right) + \frac{B}{16A}\ln\frac{(x_{in} + B/2A)}{(x_{end} + B/2A)} + \frac{C}{4B}\ln\left(\frac{x_{in}}{x_{end}}\frac{(x_{end} + B/2A)}{(x_{in} + B/2A)}\right), \tag{124}$$

where $x = s^2$ ($x_{in,end} = s^2_{in,end}$, respectively).

Using (122), we have:

$$N^* = \frac{1}{8}\left(x_{end} - x_{in}\right) - \frac{a^2}{8}\ln\frac{(x_{end} - a^2)}{(x_{in} - a^2)} + \frac{C}{4B}\ln\left(\frac{x_{end}}{x_{in}}\frac{(x_{in} - a^2 B/2A)}{(x_{end} - a^2)}\right). \tag{125}$$

According to (108), the beginning of inflation gives:

$$a^2 = 0, \tag{126}$$

and according to (122), we have:

$$\frac{B}{2A} = 0. \tag{127}$$

Then the number of e-folds is given by the following expression:

$$N^* = \frac{1}{8}(s^2_{end} - s^2_{in}). \tag{128}$$

Using the results (109)-(112), (117) and (119), we obtain:

$$N^* \simeq \frac{1}{4}\zeta v^2. \tag{129}$$

According to the "second vacuum" position (52), the VEV v in units $M_{Pl}^{red} = 1$ is:

$$v \simeq \frac{3.5 \cdot 10^{18}}{2.43 \cdot 10^{118}} \simeq 1.44. \tag{130}$$

Then

$$N^* \simeq 0.52\zeta. \tag{131}$$

Cosmological measurements give: $N^* \simeq 50 - 60$. Then Eq. (131) predicts:

$$\zeta \simeq 96 \tag{132}$$

– for $N^* \simeq 50$, and

$$\zeta \simeq 115 \tag{133}$$

– for $N^* \simeq 60$.

The values (132) and (133) for the MP parameter ζ is in agreement with estimations obtained in Refs. [66, 67], which predicted $\zeta \sim 100$. This means that cosmology is consistent with our inflationary model.

According to Eq. (109), at the beginning of inflation $\alpha = \alpha_0$ is large:

$$\alpha_0 \sim 10^3, \tag{134}$$

but λ' (see Eq. (112)) is still small:

$$\lambda' \sim 0.07. \tag{135}$$

The subsequent reasonable results follow from the consideration of the renormalization group equations (RGEs).

8 Renormalization group equations for the ordinary and mirror Higgs couplings

In the effective Higgs theory the Higgs quartic coupling will be modified to that of the Standard Models (SM and SM') as a result of the mixing term. At high energies we have the one-loop RGEs, given by Ref. [72], but now we also include the mirror s-field:

$$(4\pi)^2\beta_\lambda = (4\pi)^2\beta_\lambda^{(SM)} + \frac{1}{2}\alpha_h^2, \tag{136}$$

$$(4\pi)^2\beta_{\lambda'} = (4\pi)^2\beta_{\lambda'}^{(SM')} + \frac{1}{2}\alpha_h^2, \tag{137}$$

$$(4\pi)^2\beta_{\alpha_h} = 2\alpha_h^2 + 6\alpha_h(\lambda+\lambda') + \frac{1}{4}\alpha_h(12y_t^2 - \frac{9}{5}g_1^2 + 9g_2^2 + 12{y'_t}^2 - \frac{9}{5}{g'_1}^2 + 9{g'_2}^2), \tag{138}$$

where

$$(4\pi)^2\beta_\lambda^{(SM)} = 12\lambda^2 + \lambda(12y_t^2 - 9g_2^2 - 3g_1^2) + \frac{3}{4}g_1^4 + \frac{3}{2}g_1^2g_2^2 + \frac{9}{4}g_2^4 - 12y_t^4, \tag{139}$$

and $(4\pi)^2\beta_{\lambda'}^{(SM')}$ is given by Eq. (139) with replacements: $\lambda \to \lambda', y_t \to y'_t, g_{1,2} \to g'_{1,2}$. Eqs. (138) and (139) contain the top-quark Yukawa coupling y_t, the $U_Y(1)$ coupling constant g_1 and the $SU(2)$ coupling g_2. In order for this mechanism not to change essentially the results of Refs. [46, 49], both λ' and α_h will need to be very small so the new RGEs contributions will be minor.

We saw that near the Planck scale, parameters α_h, λ and λ' are very small, therefore the new RGE's influence is not essential for the 2-, or 3-loop results (see Refs. [46, 49]).

9 Summary and Conclusions

1. Using the Plebanski's formulation of gravity, we constructed the Graviweak Unification (GWU) model, which is invariant under the $G_{(GWU)} = Spin(4,4)$-group, isomorphic to the $SO(4,4)$-group. Graviweak Unification is a model unifying gravity with the weak $SU(2)$ gauge and Higgs fields.

2. Considering the Graviweak symmetry breaking, we have obtained the following subalgebras: $\widetilde{\mathfrak{g}_1} = \mathfrak{sl}(2,C)_L^{(grav)} \oplus \mathfrak{su}(2)_L$ – in the ordinary world, and $\widetilde{\mathfrak{g}_1'} = \mathfrak{sl}'(2,C)_R^{(grav)} \oplus \mathfrak{su}'(2)_R$ – in the hidden world. These sub-algebras contain the self-dual left-handed gravity in the OW, and the anti-self-dual right-handed gravity in the MW. We showed, that finally at low energies we have the Standard Model and the Einstein-Hilbert's gravity.

3. We discussed the existence of de Sitter solutions at the early time of acceleration era of the Universe. It was shown that in the ordinary world the VEV $v \sim 10^{18}$ GeV of "the false vacuum" is given by the relation $v = R_0/3$. Here $R_0 = 12/r_{dS}^2$, where r_{dS} is the radius of the constant curvature of the de Sitter background space.

4. We considered the Multiple Point Principle (MPP), which postulates that the Nature has the Multiple Critical Point (MCP). The MPP-model predicts the existence of several degenerate vacua in the Universe, all having zero, or almost zero cosmological constants.

5. We reviewed the Multiple Point Model (MPM) by D.L. Bennett and H.B.Nielsen. We showed that the existence of two vacua into the SM: the first one – at the Electroweak scale ($v_1 \simeq 246$ GeV), and the second one – at the Planck scale ($v_2 \sim 10^{18}$ GeV), was confirmed by calculations of the Higgs effective potential in the 2-loop and 3-loop approximations. The Froggatt-Nielsen's prediction of the top-quark and Higgs masses was obtained in the assumption that there exist two degenerate vacua into the SM.

6. In contrast to other theories of unification, we accepted an assumption of the existence of visible and invisible (hidden) sectors of the Universe. We gave arguments that modern astrophysical and cosmological measurements lead to a model of the Mirror World with a broken Mirror Parity (MP), in which the Higgs VEVs of the visible and invisible worlds are not equal: $\langle\phi\rangle = v, \quad \langle\phi'\rangle = v' \quad \text{and} \quad v \neq v'$. We considered a parameter characterizing the violation of the MP: $\zeta = v'/v \gg 1$, using the result: $\zeta \sim 100$ obtained by Z. Berezhiani and his collaborators.

7. In our model we showed that the action for gravitational and $SU(2)$ Yang–Mills and Higgs fields, constructed in the ordinary world (OW), has a modified duplication for the hidden (mirror) world (MW) of the Universe.

8. We have developed a model of the Higgs inflation using the GWU action, which contains a non-minimal coupling of the Higgs field with gravity, suggested by F. Bezrukov and M. Shaposhnikov. According to our model, a scalar field σ, being an inflaton, starts trapped from the "false vacuum" of the Universe at the value of the Higgs field's VEV $v = v_2 \sim 10^{18}$ GeV. Considering the expansion of GWU Lagrangian in powers of small values of σ/v, we get rid of the non-minimal coupling to gravity by making the conformal transformation from the Jordan frame to the Einstein frame.

9. We have used the Sidharth's prediction about the existence of the discrete space-time at the Planck scale and his idea of non-commutativity, which provides an almost zero cosmological constant. This result was applied to our GWU model of the Higgs inflation.

10. We assumed that during inflation inflaton σ decays into the two Higgs doublets of the SM: $\sigma \to \phi^\dagger\phi$.

11. Taking into account the interaction between the initial ordinary and mirror Higgs fields: $\alpha_h(\phi^\dagger\phi)(\phi'^\dagger\phi')$, we constructed a Hybrid model of the Higgs inflation in the Universe. Such an interaction leads to the emergence of the SM vacua at the EW scales: with the Higgs boson VEVs $v_1 \approx 246$ GeV – in the OW, and $v'_1 = \zeta v_1$ – in the MW.

12. We have shown that our GWU model of the Higgs inflation is in agreement with modern predictions of cosmology. We have calculated the expression for a number of e-folds N^* and have obtained the following result for the MW parameter ζ:

$$\zeta \simeq \frac{4N^*}{v^2} \simeq 100 - 115 \quad \text{for} \quad N^* \simeq 50 - 60,$$

in agreement with previous estimations predicted $\zeta \sim 100$. This means that cosmology is consistent with our GWU model of inflation.

13. We have calculated the renormalization group equations (RGEs) in the assumption that there exists the interaction between the ordinary and mirror Higgs bosons. We discussed the possibility of small values of parameters λ' and α_h with aim not to change essentially the results of the 2-, or 3-loop calculations of the Higgs mass. We assumed that near the Planck scale parameters α_h, λ and λ' (according to the MPP) are very small. Therefore, the influence of the modified RGEs is not essential for the 2-, or 3-loop results of Refs. [46, 49].

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